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Neural plasticity in the dynamics of human visual word recognition

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Abstract

Repeated exposure to words leads to plastic changes in the nervous system throughout the lifespan, with the consequence that common words are processed more rapidly and accurately than rare words. Most behavior time measures correlate highly with the logarithm of a stimulus word's experiential frequency. Here, we demonstrate similar but earlier changes in the latency of a brain-generated evoked potential recorded over the left anterior scalp as individuals silently read sentences. We conclude that experience can speed the processing of some words by at least 50 ms within the first 335 ms of visual processing. © 1998 Elsevier Science Ireland Ltd.

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Experience can change both the anatomical and functional organization of the brain at multiple scales [5]. Such plasticity depends on the brain's sensitivity to the repeated presentation of stimuli. The human word recognition system is a clear case where brain plasticity is continuous throughout life. Careful observation of human behavior reveals that people are sensitive to the powerful statistical patterns of word usage over time. People read or speak those words most rapidly which are most frequent, and these processing speed differences are proportional to the logarithms of the frequencies of the items involved [12]. This basic result holds for vocabulary items whose usage frequencies span the orders of magnitude separating the hyper-frequent 'the' from the common 'cat' from the rare 'lynx', a word that may altogether fail to occur in a million-word corpus [4]. The fact that structural properties of words co-vary with word frequency has been widely exploited recently in connectionist simulations [1]. Our facility in using words that differ so markedly in experimental frequency raises important questions about the dynamics of a system whose timing at the millisecond scale is crucial both in theory and in practice. Recent theories of both developmental reading disability [10] and language deficits in Broca's aphasia [17] have suggested that processing speed and dynamics play a prominent role in successful language comprehension.

Research on these issues has focused on the time required to perform some motor act given a verbal stimulus, but we can now examine these effects in the absence of any overt response via recordings of the electrical activity of the brain at the human scalp in the form of event-related potentials (ERPs). From these, we can determine when a word's frequency of occurrence modulates brain activity. Previous research has shown some sensitivity of the amplitude of the N400 [9] response to words in restricted circumstances [20], but reports of word frequency effects on component latency are typically in studies of the P300 in situations where a behavioral response to words as targets was required [16]. In normal reading or listening, however, words are not targets for detection but sources of linguistic information.

While most word types in the language are in the so-called open class (e.g. content words), the vast majority of highly frequent words are closed class items (i.e. function words). Thus the search for a word-frequency-specific shift in component latency for all words must directly address the possible confounding differences due to lexical class [13].

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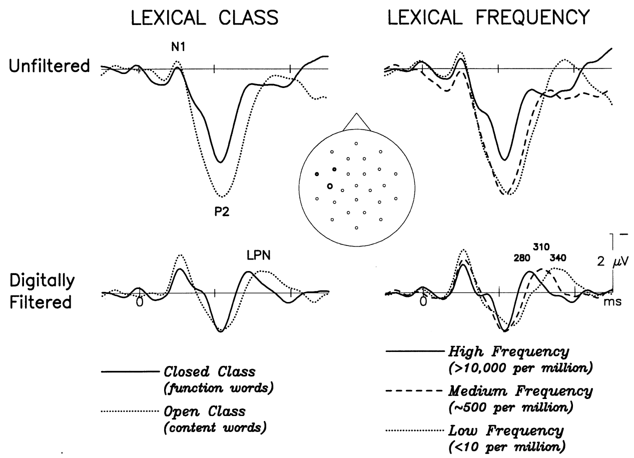

Fig. 1. Upper panel: grand mean ERPs ($n = 21$) showing the effects of word frequency and lexical class on the waveforms at a left anterior electrode site marked with a large bold circle on the diagrammatic head; the N1 and P2 components are labeled on the lexical class trace. Lower panel: same data as in upper, but digitally high-pass filtered at 4 Hz.

Moreover, it is important not to confuse the effects of word length and word frequency on the brain's electrical response, since the correlation between these two factors is often quite high ($r > 0.9$ in many texts), thereby making it difficult to estimate separate effects for either variable alone [14]. These confounds can be overcome, however, by examining a subset of data where the two variables are less confounded.

In the present experiment, ERPs were recorded to words presented in normal sentence contexts with a word duration of 200 ms and a word onset asynchrony of 500 ms as subjects read for comprehension. Comprehension was tested by having subjects make true/false judgments about short test statements following 50% of the experimental sentences. The 21 participants were all young, healthy native English speakers receiving course credit or payment for their participation in the experiment. The raw EEG was bandpass-filtered between 0.01 and 100 Hz and digitized at a rate of 250 Hz. The electrode array consisted of 26 scalp channels and the right mastoid referenced to the left mastoid; the data was later algebraically re-referenced to the average of the two mastoids. Blinks and eye movement artifacts were detected using electrodes placed below both eyes and at the outer canthi, and trials with such artifacts or channel blocking were excluded from all averages.

Fig. 1 shows the patterns of data obtained from ERPs evoked during silent word-by-word sentence reading for words of varying frequency and word class. As shown in the upper panels, the latency of a left anterior negativity does seem to vary with word frequency, but this is difficult to see given the differences in the ERPs to different word classes. However, as shown in the lower panel, digital filtering of the ERP data (high pass > 4 Hz) can isolate a negativity that systematically varies with word frequency. This filtering isolates the morphology of a frequency sensitive negativity (FSN) from the temporally overlapping components whose frequency content is more strongly biased to lower frequencies. Fig. 1 also shows that the latency varies and is correlated with lexical frequency while its amplitude does not distinguish between lexical classes. Similarly reliable data can be obtained from each site rendered in bold on the head. The minimum number of trials per participant for each waveform is 127.

The latency of this negative component was measured for a series of narrow frequency bins and regressed onto word scarcity and word class as shown in Fig. 2. Scarcity is a linear transformation of log word frequency normalized to the size of the corpus (i.e. $6 - \log_{10} F$, where F is frequency of occurrence in a million-word corpus). This transformation insures that the predictor is positively rather than negatively correlated with the latency of both the FSN and behavioral reaction time measures. Our analysis indicates that the form of the relationship between FSN latency and scarcity is linear, just as for gaze duration [7]. As suggested in the left panel of Fig. 2, the latency-scarcity relationship does not depend on lexical class; thus, in the middle panel the data are plotted collapsed over lexical class and the best-fit line, whose formula is: FSN latency (ms) = $274 + 11 \times S$, where S represents scarcity. This regression accounts for 92% of the variance in grand mean latency. The right panel reveals that the relationship between FSN latency and word frequency holds for data from individual subjects as well. Although low scarcity words are all closed class and high scarcity words are all open class, additional regression analyses showed that lexical class was not a significant independent predictor of FSN latency ($P > 0.25$). Likewise FSN latency is not due to systematic differences in word

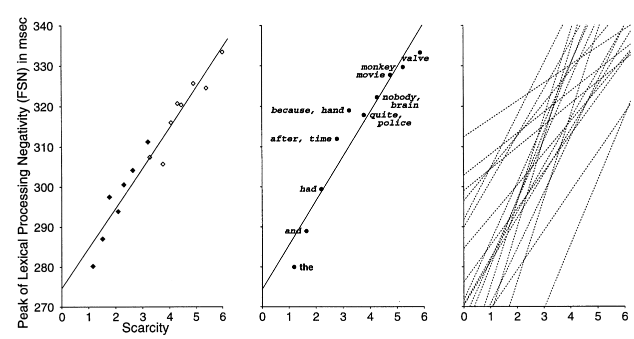

Fig. 2. Left: grand mean FSN latency for 15 frequency-based word bins plotted against scarcity. Bins were of approximately equal size (190 pre-rejection items) except the least, (containing ERPs elicited by 'the'; a minimum of 377 trials per subject) and the most scarce bin (containing a minimum of 390 trials per subject of all scarcity = six words). Word classes containing only closed class items are plotted with filled diamonds, open class items are plotted with open diamonds. Middle: same data shown in the left panel collapsed over word class at equally spaced intervals of scarcity (minimum number of items per bin = 198). Points are labeled with representative lexical items from each frequency class; classes containing both closed and open class words are double-labeled. Right: regression lines relating FSN latency to scarcity for bins defined in the middle panel for 19 individuals whose regression lines were significant at the $\alpha = 0.10$ level.

length, as a multiple regression analysis on the largest subset of data (16 bins) whose correlation was below 0.4 (r = 0.34) indicated that length in characters accounted for an (unreliable) 3% of the variance when the effect of word frequency was taken into account, and never more than 22% even when it was the only predictor. The right panel of Fig. 2 demonstrates that these effects hold in single subjects despite the decrease in signal-to-noise ratio; the mean amount of variance accounted for across all 21 subjects was 58%. We therefore conclude that the FSN latency is affected by the relative scarcity of a word in daily usage, and not by either word class or orthographic length.

To assess whether the FSN is in fact a constant feature of the ERP independent of word class, we compared the radial current source density (CSD) of the FSN for open and closed class words, as shown in Fig. 3. The remarkable similarity of these CSDs (Fig. 3) indicates a consistent configuration of neural generators for them. The presence of multiple sources and sinks in these maps implicate several neural generators active during the temporal window overlapping generation of the FSN. However, analyses of other components maximal at different electrode sites have not revealed any reliable latency modulations related to word frequency.

The specific neural generators of the FSN are as yet unknown, and cannot be located in principle without auxiliary assumptions or converging data from other imaging modalities. However, the results of various functional imaging studies of visually presented words [15] or sentences [8], and the generation of volitional eye movements [3], all point to areas within the frontal cortex that are active in reading, although possible generators in the anterior temporal lobe cannot be ruled out. Specific effects of word frequency were not found in left frontal areas in a recent positron emission tomography (PET) word-naming study [2], but PET or functional magnetic resonance imaging studies that contrast activations caused by high and low frequency words may not be ideal for localizing the generator of an ERP component like the FSN whose latency is variable but whose amplitude is constant. Our finding that word frequency affects FSN latency much as it affects gaze duration leads us to hypothesize that the neural generators of the FSN also could be involved in volitional gaze regulation during normal reading.

More information about what brain structures may contribute to the observed latency shift of the FSN can be gleaned from the time course and presumed neural generators of various visual ERP components including the C1, P1, and N1 [6]. The C1 component, with a peak latency of ~70 ms, appears to have a generator in V1. The earliest visual component sensitive to manipulations of spatial attention is the P1 (peak latency ~100 ms), which has extra-striate generators that probably include at least V2 and V4. Components in the N1 family (latencies ranging from 140 to 180 ms) vary with attentional manipulations of features such as spatial location, color, and motion, consistent with localizations in V3, V4, MT/V5 and other inferotemporal areas. The earliest known visual ERP sensitive to the difference between real words and random letter strings is a posterior positivity peaking around 150 ms, which has been linked to similar activity in the posterior fusiform gyrus [18]. The latency of the frontally distributed FSN is sensitive to experiential word frequency and has a broad peak latency range from 280 to 335 ms post word onset (see, e.g. Fig. 2).

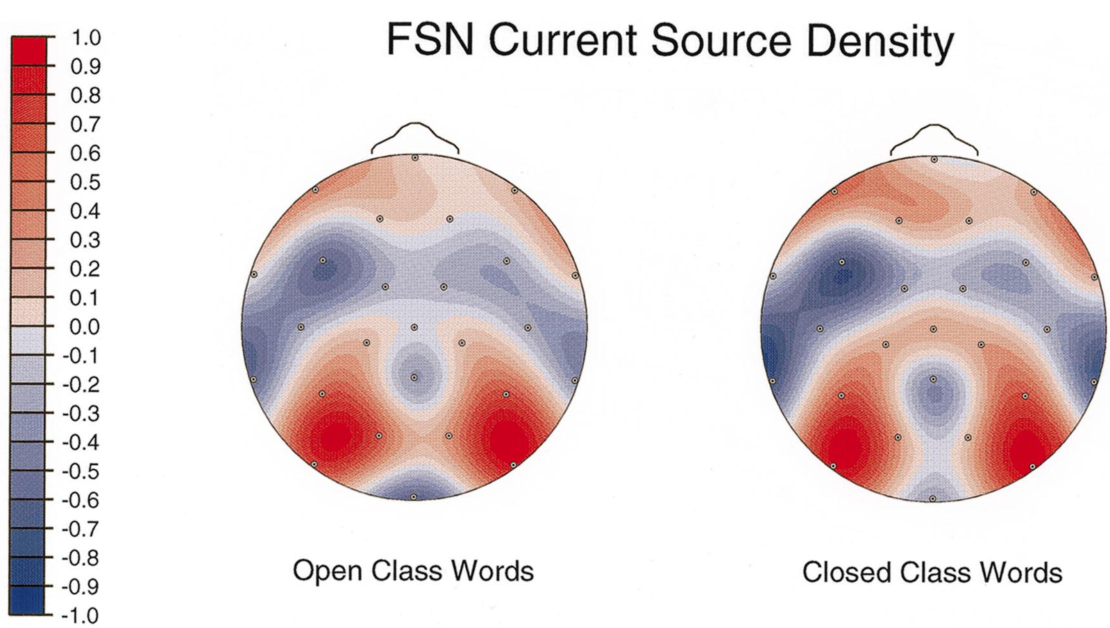

Fig. 3. Normalized current source density (CSD) of the digitally filtered ERP in an 8 ms wide window around the average peak latency of the FSN in grand mean data for open class (LPN latency of 330 ms, maximum 1936 words per subject) and closed class (280 ms, maximum 1713 per subject) words. The same scale is used for both types; current sinks are blue, current sources are red, and small white circles indicate electrode locations.

If we discount the possibility of processing latency effects in the pre-striate visual pathway, this chronology suggests that the visual and language pathways between V1 and the generators of the FSN are traversed in at most 275 ms by the least common words in the language, while the same pathways appear to be traversed by the experientially most common words in at most 220 ms. This is a 20% improvement in processing time. The net reduction due to experience might be even larger, given that the earliest known stage in visual processing where any word/non-word distinctions are seen occurs about 90 ms after the first observable activity in V1.

In summary, we have discovered a brain potential maximal over left anterior regions of the scalp whose latency is closely correlated with both the normative frequency of words in text and gaze duration in normal reading, even though the eyes remain fixed in our experiments. From the relative insensitivity of the FSN to word length or lexical class we infer that it is unlikely to reflect processes related to stimulus encoding or syntactic processing per se, although some recent models of syntactic processing include a more prominent role for item frequency-based information [11]. More generally, we do not yet know whether the effect of frequency on the latency of the FSN derives from an encoding of item frequency in a unitary memory trace or from the accumulation of multiple frequency effects as processing cascades throughout the nervous system. The fact that the FSN itself, unlike other ERP components possibly generated nearby on the cortex [13], does not reflect lexical class differences reinforces our view that there are multiple and parallel processing streams within the language processing system, at least one of which exhibits plastic changes in processing speed due to differential experience. Indeed, this might be seen as evidence in favor of a functional dissociation between words that differ in word frequency, even though they may be processed in identical neural tissue. This is consistent with computational models that recognize a form of 'dynamic modularity' [19] and indicates the usefulness of non-invasive ERP measures in relating neural plasticity to the real-time dynamics of cognitive processing.

[1] Elman, J., Bates, E., Johnson, M., Karmiloff-Smith, A., Parisi, D. and Plunkett, K., Rethinking Innateness: A Connectionist Perspective on Development, MIT Press/Bradford Books, Cambridge, MA, 1996.
[2] Fiez, J.A., Balota, D.A., Raichle, M.E. and Petersen, S.E., The effects of word frequency and spelling-to-sound regularity on the functional anatomy of reading, Soc. Neurosci. Abstr., 19 (1993) 1808.
[3] Fox, P.T., Fox, J.M., Raichle, M.E. and Burde, R.M., The role of cerebral cortex in the generation of voluntary saccades: a positron emission tomographic study, J. Neurophysiol., 54 (2) (1985) 348–369.
[4] Francis, W.N. and Kucera, H., Frequency Analysis of English Usage: Lexicon and Grammar, Houghton Mifflin, Boston, MA, 1982.
[5] Greenough, W.T. and Chang, F.F., Plasticity of synapse structure and pattern in the cerebral cortex. In A. Peters and E.G. Jones (Ed.), Cerebral Cortex, Vol. 7, Plenum, New York, 1988, pp. 391–440.
[6] Hillyard, S.A, Teder-Sälejärvi, W.A. and Münte, T.F., Temporal dynamics of early perceptual processing, Curr. Opin. Neurobiol., (1998) in press.
[7] Just, M.A. and Carpenter, P.A., A theory of reading: from eye fixations to comprehension, Psychol. Rev., 87 (1993) 329–354.
[8] Just, M.A., Carpenter, P.A., Keller, T.A., Eddy, W.F. and Thulborn, K.R., Brain activation modulated by sentence comprehension, Science, 274 (1996) 114–116.
[9] Kutas, M. and Hillyard, S.A., Reading senseless sentences: brain potentials reflect semantic incongruity, Science, 207 (1980) 203–205.
[10] Livingstone, M.S., Rosen, G.D., Drislane, F.W. and Galaburda, A.M., Physiological and anatomical evidence for a magnocellular defect in developmental dyslexia, Proc. Natl. Acad. Sci. USA, 88 (1991) 7943–7947.
[11] MacDonald, M.C., Pearlmutter, N.J. and Seidenberg, M.S., The lexical nature of syntactic ambiguity resolution, Psychol. Rev., 101 (1994) 676–703.
[12] Monsell, S., Doyle, M.C. and Haggard, P.N., Effects of frequency on visual word recognition tasks: where are they?, J. Exp. Psychol., 118 (1989) 43–71.
[13] Neville, H.J., Mills, D.L. and Lawson, D.S., Fractionating language: different neural subsystems with different sensitive periods, Cerebral Cortex, 2 (3) (1992) 244–258.
[14] Osterhout, L. and Bersick, M., Brain potentials elicited by words: word length and frequency predicted the latency of an early negativity, Biol. Psychol., 46 (2) (1997) 43–168.
[15] Petersen, S.E. and Fiez, J.A., The processing of single words studied with positron emission tomography, Annu. Rev. Neurosci., 16 (1993) 509–530.
[16] Polich, J. and Donchin, E., P300 and the word frequency effect, Electroenceph. clin. Neurophysiol., 70 (1988) 33–45.
[17] Prather, P., Zurif, E., Stern, C. and Rosen, T.J., Slowed lexical access in nonfluent aphasia: a case study, Brain Lang., 43 (1992) 336–348.
[18] Schendan, H.E, Ganis, G. and Kutas, M., Neurophysiological evidence for visual perceptual categorization of words and faces within 150 ms, Psychophysiology, (1998) in press.
[19] Tanenhaus, M.K., Dell, G.S. and Carlson, G., Context effects in lexical processing: a connectionist approach to modularity. In J.L. Garfield (Ed.), Modularity in Knowledge Representation and Natural-Language Understanding, MIT Press, Cambridge, MA, 1987, pp. 83–108.
[20] Van Petten, C. and Kutas, M., Influences of semantic and syntactic context on open and closed class words, Mem. Cognit., 19 (1991) 95–112.